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WIND POWER

G. Lacroix

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16. Abstract

Both classical and theoretical methods for preventing wind engines from overspeeding are described.

The greatest drawback in the use of these devices is seen to be their inability to compete with other power sources on an economic basis. In this connection there is a detailed description of the failure of the Grandpa's Knob experiment conducted in Vermont in the early 1940's: the technical defects were minor in comparison to the lack of economic feasibility.

Russian efforts -- still largely in the research stages at the time -- and Danish projects -- primarily low-power -- are discussed briefly.

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G. Lacroix

The first part of this article began an examination of the various types of wind machines: panemones, turbines, and engines with horizontal shafts and radial blades. This examination is completed below, and consideration is given to the economic problems involved in the large-scale use of wind power. /105*

II. Study of the Various Types of Machines

Engines with Horizontal Shafts and Radial Blades (cont.)

Power or Speed Control

Another problem of equal importance is that of controlling the power or speed. To operate at maximum efficiency, a fixed-blade wind engine should rotate at a speed proportional to that of the wind. It thus develops an amount of power which varies as the cube of the wind speed. Since, because of the cost price entailed, there is no possibility of producing blades and generators of a size permitting them to operate under the maximum wind force which can be anticipated, devices must be provided to limit the power and speed of the wind engine when the speed of the wind exceeds the value for which the installation was calculated. An additional problem occurs with ac installations using alternating generators whose rotation speed must remain constant. Since a fixed-blade wind engine operates under poor conditions at constant speeds, control devices must be provided on the blades.

Some of the proposed devices for limiting the power or the speed act directly on the power produced by the blades by changing

*Numbers in the margin indicate pagination in the foreign text.

either their surface area or their angle of attack. Control of the surface area by means of sections of cloth extended over wooden frames in varying degrees was the common solution for the old flour mills seen in our countryside. Among the more widely used solutions the Berton blades should be mentioned; these consist of longitudinal slats which cover each other more or less completely on the principle of a fan (Fig. 15). The blades used in the Mammouth wind engine (Fig. 16) should also be noted; here each blade includes numerous small shutters rotating around perpendicular axes in the general direction of the blade. The disadvantages of these types of machines are the difficulty of having the angle of attack vary from the center to the tip of the blade and the fact that they necessitate a large number of joints which are exposed to the weather.

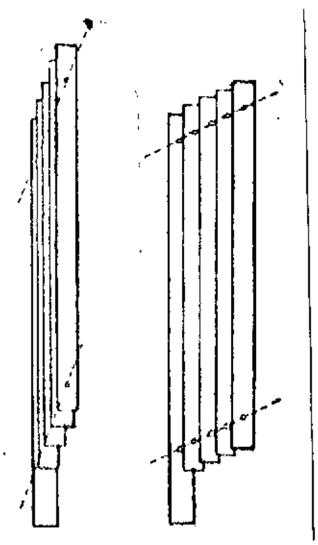

Fig. 15. Berton blade with surface area variable by means of longitudinal slats: a. retracted; b. open.

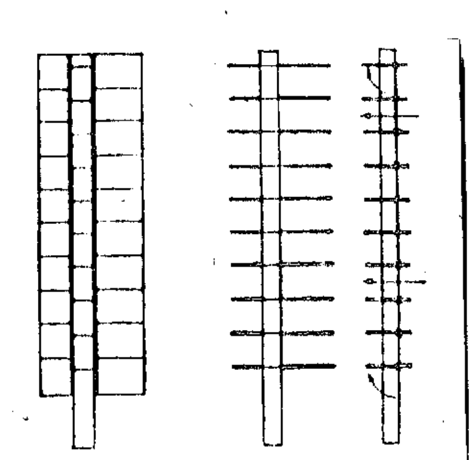

Fig. 16. Mammouth blade with surface area variable by means of transverse shutters: a. open; b. retracted, front view; c. retracted, side view.

The best solution consists in the use of movable blades, that is, blades whose angle of attack can be changed as a function of the wind speed. In small installations, especially those using direct current, the main concern is to limit the overdrive speed to a level which will not be dangerous. The solution consists in the use of simple devices which directly utilize the centrifugal force of the blades to vary the angle of attack (Figs. 17a-b). In large installations, especially those using alternating current, which must operate at constant speeds, the blades are controlled by servo motors which are dependent on a speed regulator (Fig. 18). The solutions used are the same as those used to regulate hydro-electric turbines, and they may be assumed to be completely developed by this time.

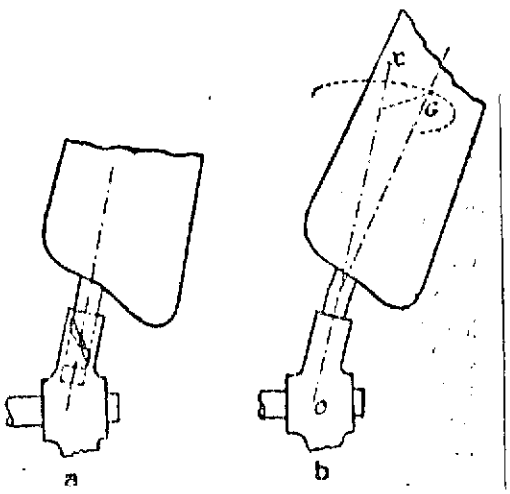

Fig. 17. Examples of variable-incidence blades controlled by centrifugal force: a. The cylindrical tip of the blade rotates and slides within a socket in the hub having an elongated thread or a helicoidal ramp. b. The tip of the blade is bent in such a way that the center of gravity G is not located on the axis of orientation OX.

The control process consisting in displacement of the entire wind engine need only be mentioned in passing, since this process is inapplicable to the high-power wind engines with which we are concerned by reason of its excessively low speed.

In other control processes which are applicable to fixed-blade wind engines, increases in speed and useful power are prevented by dissipating the surplus energy in the form of additional friction in the air produced by active surfaces such as Renard vanes. These surfaces are normally retracted and are positioned perpendicular to the wind, usually in response to centrifugal force, only when the rotation speed of the wind engine exceeds a given value. They are attached direct-

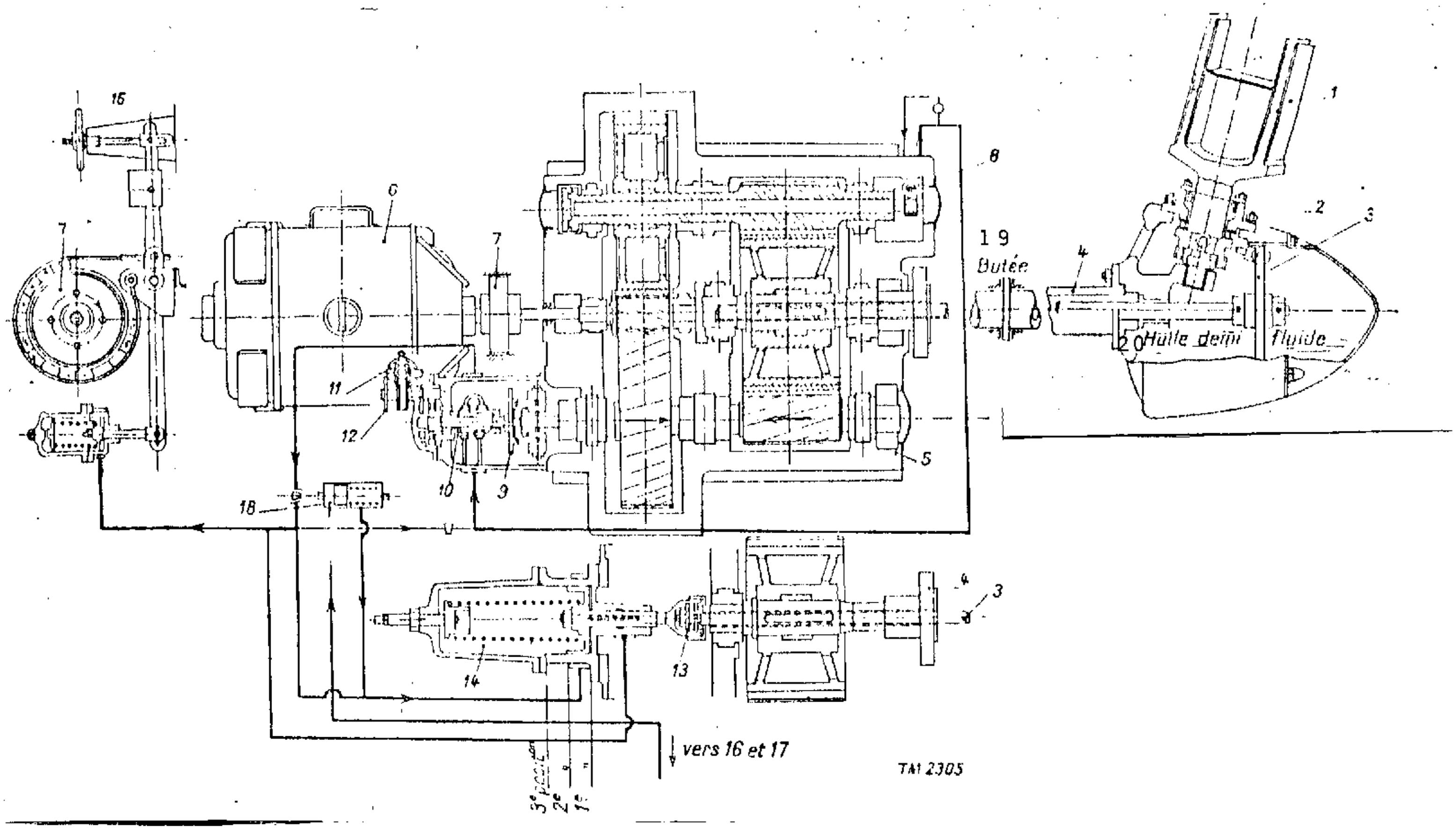

Fig. 18. Schematic diagram of a fuel oil-driven servo motor studied by the Electro-mechanics Company in 1932. This device keeps the speed of the asynchronous generator virtually constant; it automatically releases a safety brake if there is an abnormal increase in speed. An analogous device was provided for the wind engine in Fig. 25.

1. Movable blades. 2. Ball bearing. 3. Guided platform turning the blades ± 30°. 4. Hollow shaft. 5. Double multiplcation gear box. 6. Generator. 7. Oil-controlled band brake. 8. Oil pump. 9. Centrifugal regulator controlling internal valve. 10. Double valve. 11. Electric servo motor controlling external valve. 12. Manual wheel controlling external valve. 13. Ball-bearing swivel. 14. Piston orienting the blades. 15. Manual brake lock. 16. Oil tank. 17. Oil pump with motor-controlled gears for stopping (may be mounted on the platform). 18. Oil-driven stop motor. 19. Thrust bearing. 20. Semi-fluid oil.

ly to the blades (Fig. 19a) or mounted on special arms in the spaces between the blades (Figs. 19b-c). Another device includes a small longitudinal shutter controlling the entire length of the blade and normally incorporated into its structure. This shutter is extremely effective since it not only acts as a brake, but also disturbs the airflow around the blades and thus reduces their motive force. All these control devices by energy dissipation have so far been used only to limit the overdrive speed of wind engines. They may also be controlled by servo motors, however, to accomplish speed or power regulation.

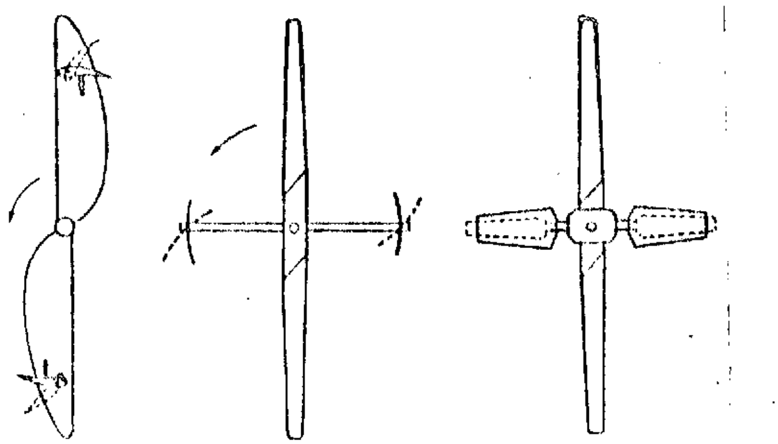

Fig. 19. Examples of speed control by means of braking shutters.
a. Ventimotor (Bilau). b. Wincharger. Paris-Rhône.

Finally we should note an extremely attractive control process developed by M. Darrieus, Member of the Institute, which has been successfully used in wind engines 8, 10 and 20 m in diameter which were constructed from 1927 to 1931 by the Electromechanics Company (Figs. 20-22). This solution consists in giving the electrical generator a highly accentuated shunt or compound characteristic in addition to the speed corresponding to maximum charge, in such a way that its resistant torque increases much faster than the motor torque of the blades as a function of the speed of rotation. Under these conditions the wind engine is no longer able to rotate at a speed proportional to that of the wind. In other words, the u/v ratio decreases as v increases. The angle of attack of the relative wind thus increases until the air currents begin to separate into layers behind the blades. The blades no longer "carry," automatically limiting the speed. This is one of the simplest control methods, since it is limited to an adaptation of the characteristics of the generator and permits the use of fixed blades.

This method may be criticized in that it makes the safety of the control system depend on the existence of resistant torque in the generator, even though this torque may fail if one of the fuses melts or there is a break in the network. In these cases the wind engine could be kept from reaching a dangerous speed only by the immediate application of a mechanical brake of sufficient power.

III. Economic Considerations

This necessarily brief and incomplete review of the most important problems raised in the design of high-power wind engines shows that technical solutions for these problems do exist, some of them having been available for some time. From a technical standpoint, therefore, there is nothing to prevent the immediate construction of high-power wind engines, at least to a maximum of 1,000 kW. The only problems which could be encountered are economic in nature; one should not attempt to disguise their seriousness, however. Even though wind is supplied in unlimited quantities free of charge, it does not necessarily follow that the power supplied by a wind engine will also be free. Especially because of the fact that they are not mass-produced, wind engines are costly to build and maintain. Furthermore, the high-power units are somewhat more costly due to the complicated devices (movable blades, servo

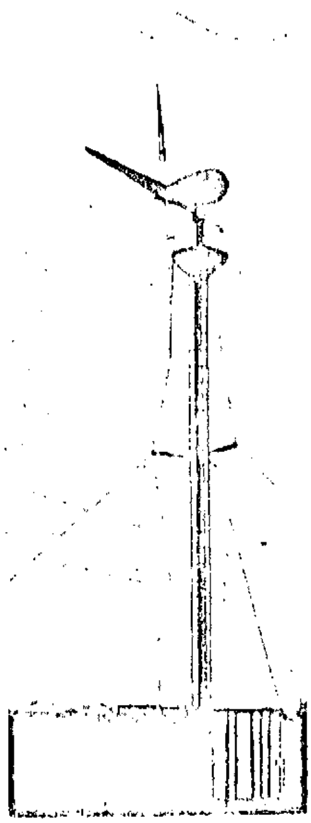

Fig. 20. Wind engine 8 m in diameter mounted on a wooden post (Electromechanics Company, 1927).

This device includes four two-sided wooden blades placed at intervals. Power: 2 kW at 60 rpm in a wind of 6 m/sec.

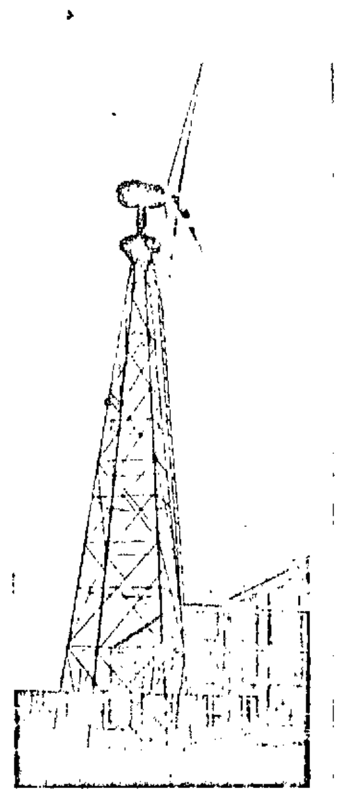

Fig. 21. Wind engine 10 m in diameter mounted on a metal pylon (Electromechanics Company, 1930).

This device includes three hollow soldered sheet metal blades. Power: 4.5 kW at 90 rpm in a wind of 6 m/sec.

motors, etc.) which they require. The small amount of data available on the cost price of the 1,000 kW installation built in the U.S. shows that the cost per kW installed is double that of a hydroelectric plant of the same power capacity; mass production would barely lower this cost to that of hydroelectric plants. This costly initial outlay weighs heavily on the cost price of the electrical power produced. According to information on the Wime D 12 wind engines 12 m in diameter which have been built in Russia [1], the cost price per kWh at the generator terminals is 20 kopeks for an average wind speed of 5 m/sec and 15 kopeks for an average speed of 6 m/sec, while this cost is only 5 to 6 kopeks for large thermal plants.

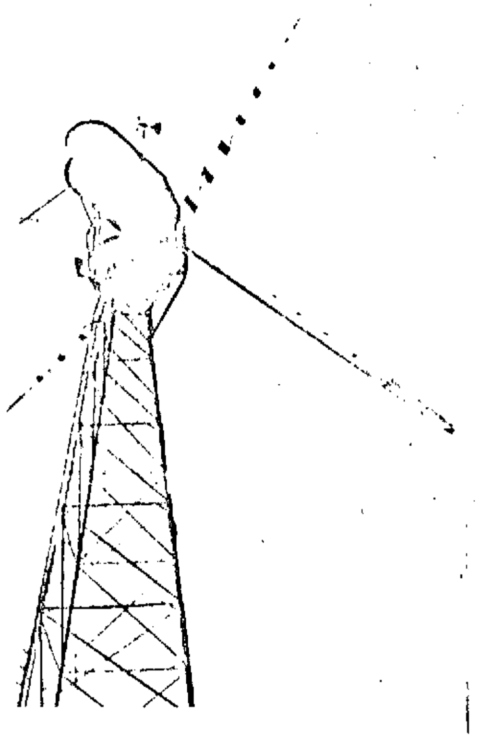

Fig. 22. Wind engine 20 m in diameter mounted on a 20 m pylon (Electromechanics Company, 1929).

Three hollow welded sheet metal blades. Power: 15 kW at 50 rpm in a wind of 6 m/sec. This device delivers the power to an alternating network by means of an ac-dc converter unit.

Another factor against the wind engine is the intermittent and irregular nature of its motive force, which makes it necessary to provide either means of energy accumulation -- which frequently must be extensive — or a backup engine. In developed countries such as our own the wind engine can scarcely be expected to compete with other sources of power such as the electricity network or the internal combustion engine. In fact, before the war the cost of a wind engine was as much as three to five times that of an electricity-producing unit using a gasoline engine. The fuel expenditure was considered secondary to the advantages offered by this type of engine: constant availability, ease of transport, etc.

Low- and moderate-power wind engines thus appear to be viable only in countries of colonial type, that is, countries where the motive force is to be supplied to rural areas at a considerable distance from municipal centers and where the transportation of fuel over large distances considerably increases its cost price.

It is not surprising, therefore, that the use of wind engines is especially widespread in countries such as North America and Russia. Moreover, in the U.S. it is especially common to see low-power units (a few hundred watts) used for illumination and recharging batteries at radio receiving stations (the Windcharger Company alone has apparently supplied more than 500,000 of these units), while in Russia these units are also commonly used to supply motive power to large agricultural projects, resulting in the use of more powerful devices ranging from 12 to 30 meters in diameter.

The conditions are hardly more favorable for the solution of operating a wind engine and an electrical network in parallel; this has frequently been recommended as a means of avoiding the high installation and maintenance costs of a series of storage batteries. In most cases the possibility of installing a wind engine in a rural installation is considered only because the cost of connecting the area to an electricity network is prohibitive (long lines, transformers, etc.). If the area must be connected to the network anyway, the installation of a wind engine is no longer justifiable unless it offers some economic benefit to the owner, that is, if the electrical company agrees to pay a reasonable price for the additional power supplied to its network by the wind engine. Now, even disregarding the tendency of some networks to view these small installations as competition which should not be encouraged, and the technical problems raised by parallel operation, it must be recognized that the irregular and intermittent nature of the power thus supplied to the network will not make it possible for the electrical company to pay for this power at a price which affords adequate compensation.

The reason for which moderate- and high-power installations are being developed only at a very slow rate can be found precisely in this inability of the wind engine to compete with other energy sources from an economic standpoint. In fact, it has not been possible for the Electromechanics Company to complete any of the installations it has researched for North Africa since 1935, ranging from a pumping unit 7 m in diameter with electric transmission (Figs. 23 and 24) to a three-phase 50 kW generating unit 30 m in diameter (Fig. 25), since the purchase price was invariably found to be prohibitive in comparison to the amount of power produced, given the aleatory and unpredictable nature of energy supply.

The conditions might become more favorable if wind power is used by the electrical companies themselves. With their financial resources they could undertake the research and construction of high-power wind plants without being stopped by the problems of all types which invariably occur during the development of so new a type of equipment, and which until now have discouraged individual inventors or industrial companies incapable of extending their financial outlay over a long enough period to overcome initial failures. These plants would no longer compete with, /109 but would complement, the company's other thermal and hydroelectric plants, since wind energy is at a maximum in our part of the world just at the time when the power available from watercourses is at a minimum. Since the conditions for installation are independent of the site it would be necessary to provide only a very small number of standardized mass-produced models, and a more or less large number of these units could be installed at selected locations. The greater the number of plants installed, the greater the advantages in terms of the reliability of the power produced.

Obviously, the construction of wind-powered electrical plants will be possible only if the cost price per kilowatthour produced is comparable to that for hydroelectric or thermal plants. Now, this price depends directly on the wind system involved, which determines not only the diameter of the wind engine, but also the

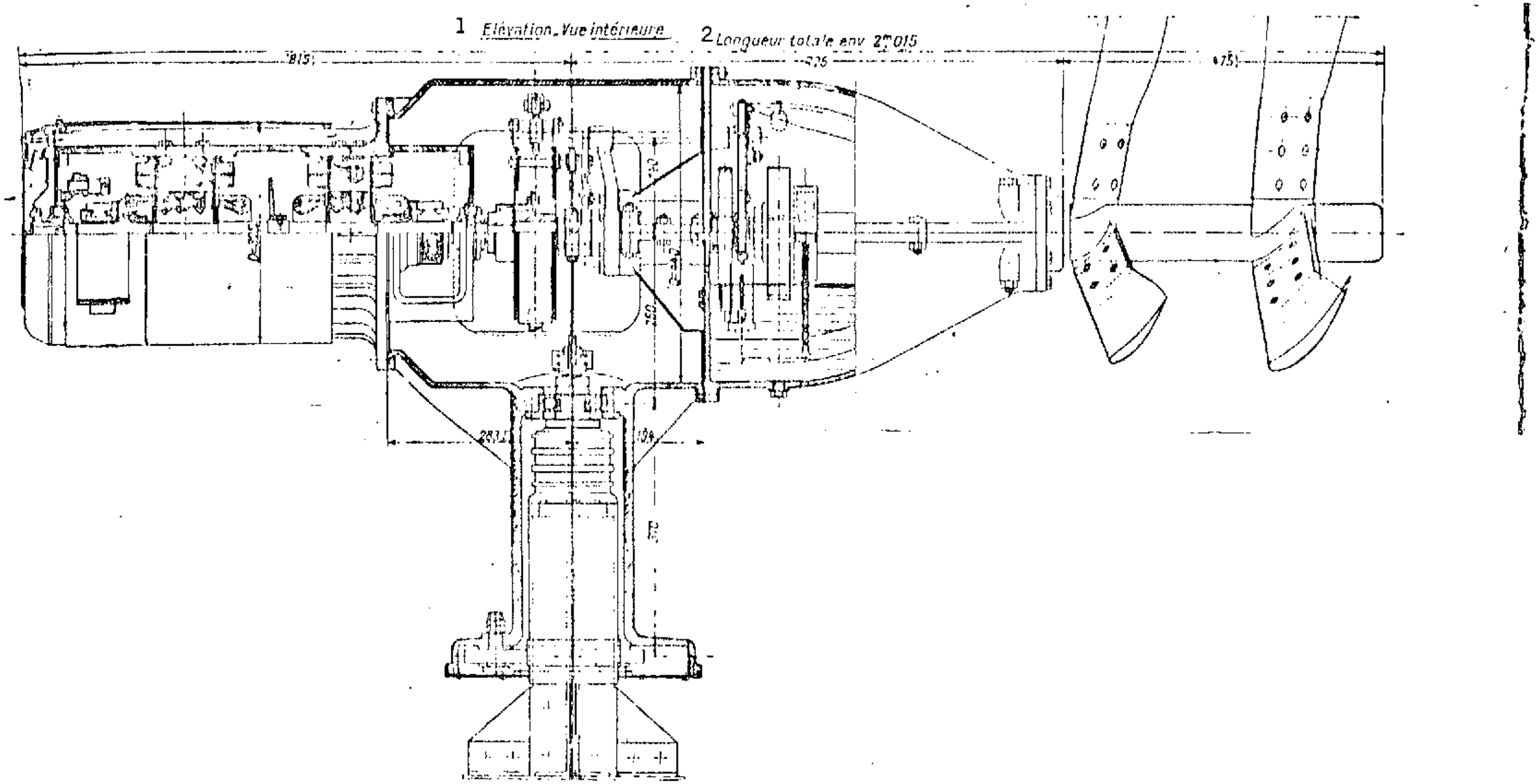

Fig. 23. Electric transmission pumping unit studied in 1935 and again in 1941 by the Electromechanics Company.

Left to right: specialized exciter, generator, safety brake, multiplier and hub. Three fixed blades 7 m in diameter. Impervious to sand.

Key: 1. Height: interior view. 2. Total length app. 2.015 m.

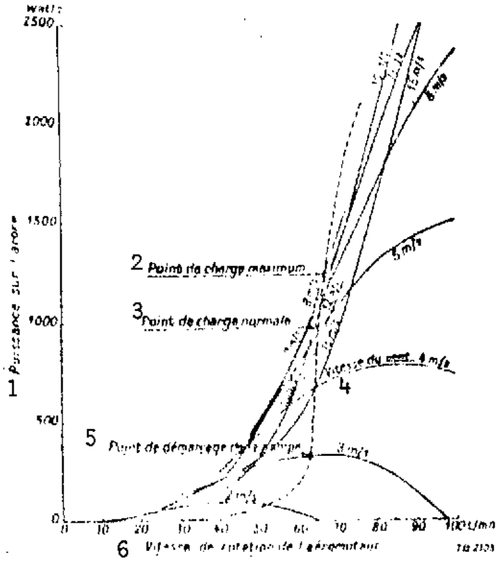

Fig. 24. Mechanical characteristics of the pumping unit shown in Fig. 23. Due to the nature of the special exciter, the power on the shaft increases very quickly once the rotation speed exceeds 63 rpm. The pump is set in motion by a 3 m/sec wind and the point of normal operation (950 W) is reached at a little more than 5 m/sec; maximum power (1,250 W) is reached at 8 m/sec and then decreases to 650 W at 15 m/sec.

Key: 1. Power on shaft.
2. Point of maximum charge.
3. Point of normal charge.
4. Wind speed.
5. Starting point for unit.
6. Rotation speed of wind engine.

number of hours of operation per year. Computation of the cost price thus presupposes a thorough knowledge of the wind system Data furnished by meteorological stations are of little use, since they are usually limited to an indication of the average and maximum speeds. Since the power produced by a wind engine varies with the cube of the wind speed, the data required are not the average of the speeds, but the average of the cube of the speeds. This factor obviously may be obtained by computation on the basis of instantaneous speed curves given by recording anemometers. These devices are relatively costly, however, and few stations are equipped with them. It would be easier to use devices directly integrating the cube of the speeds.

Only when knowledge of the wind systems in France is complete will it be possible to determine whether or not high-power wind electrical plants would be viable in this country. This problem has not escaped the attention of our large electric companies.

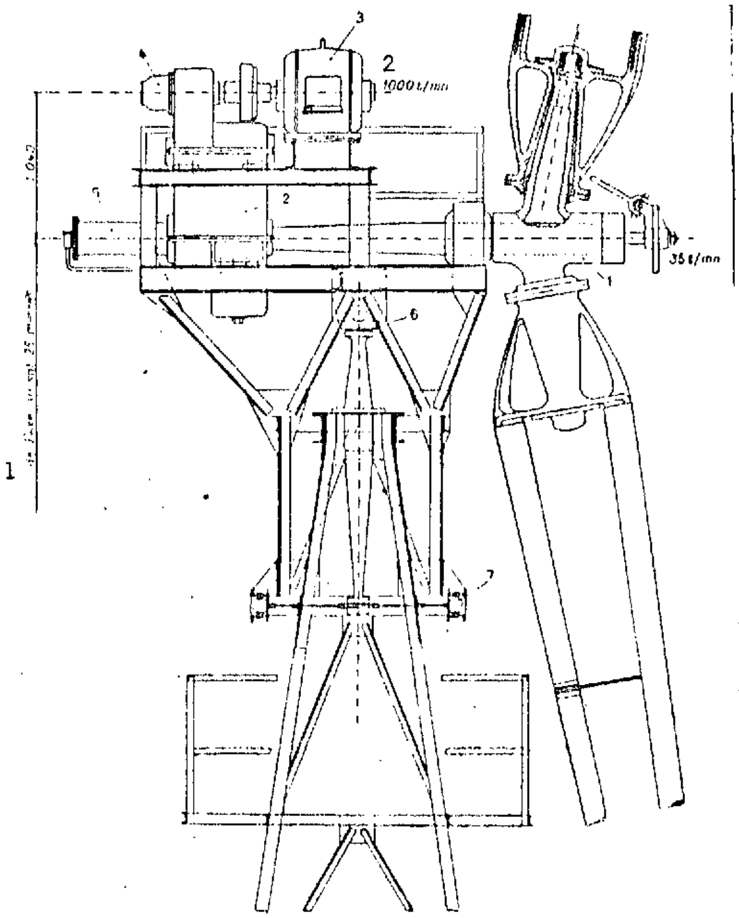

Fig. 25. Wind engine 30 m in diameter for direct production of alternating current. (Electromechanics Company, 1935).

This device includes three biplanar blades whose orientation is controlled by an oil-driven servo motor. Power: 43 kW at 35 rpm with a wind speed of 6 m/sec. Biplanar blades constructed of hollow sheet metal, hub, multiplying gear 35/1000 rpm, asynchronous generator, oil cylinder controlling the blades, upper pivot, ring of rollers.

Key: 1. From axis to ground: 25 m. 2. 1,000 rpm (typ.).

In his extremely valuable study [2], P. Ailleret has very successfully extracted the essential data and has demonstrated the value of knowing the amount of power produced per square meter of surface subjected to wind per year before attempting any research on or construction of a wind engine.
He proposes that the large power distribution companies immediately undertake the indispensable research on the wind systems, installing integrated windmills in as many locations as possible which will make it possible to determine the amount of power which would be supplied by a wind engine at the same site. This suggestion was favorably received by the electrical subsidiaries and subsequently by the French Electrical Company; the necessary integrators were built and installed at various points in France and readings are currently being taken.

Whatever conclusions may be drawn from this investigation, it will at least have had the merit of constituting the first serious effort toward the large-scale use of wind power in France. One can only hope that results will soon be forthcoming.

Furthermore, several foreign countries have already surpassed us in the construction of wind-powered electric plants linked to a public distribution network. We will not expand on the Russian and Danish projects already described in the present article [3]. However, it might be mentioned that the installation at Balaklava (three blades, 30 m in diameter, 100 kW) does not seem to have been satisfactory. According to the journal Elektritchestvo (No. 2, 1940), "It is difficult to construct the mechanical part so as to assure safe operation. These installations have been found to be less economical than those productive of less power." This quasi-failure is probably at the basis of the abandonment of the 10,000 kW power plant project which was to be built at Ai-Petri in Crimea. On the other hand, satisfactory results have been obtained with units 12 m in diameter (12 kW at 8 m/sec) built by the Petrowski plant in Cherson. It has been predicted that beginning in 1943, the Russian plants will annually turn out 28,500 power units of all types with a power capacity of 120,000 kW, capable of supplying 312,000,000 kWh per year with a wind speed of 5 m/sec.

At the present time Denmark undoubtedly has the largest number of wind power plants. Since 1941 there have been 65 installations producing about 260,000 kWh per month. Generally these are Mammouth four-blade wind engines of 14½, 16 and (most often) 18 m in diameter, with a maximum power of 30 kW. The amounts of power produced have reached a maximum of 6300 kWh per month at the Roerslev plant (September 1941) and 518 kWh per day at the Skamby plant (January 31, 1941). The Danish installations therefore show that electrical power can be produced by wind engines at an acceptable cost price. These are primarily low-power installations, however, supplying dc networks which are not very extensive (community networks, for the most part), and consequently do not furnish very convincing data on the construction of high-power ac plants.

Thus it seems preferable to spend more time on a discussion of the American plants and research. The 1,000 kW wind engine at /110
Grandpa's Knob [4] (Fig. 26) installed in 1941 near Rutland, Vermont, was the object of considerable expectation at the time it was built. It consisted of a drive wheel with two blades 53 m in diameter, using a multiplying gear train to drive a 1,000 kW alternating generator at 600 rpm. The blades, with a variable angle of attack, were controlled by a servo motor which kept the rotation speed virtually constant. In addition the blades were able to fold down in the direction of the wind to give way before gusts. Each blade weighed 7 T. A transformer linked the alternating generator to the 44,000 V distribution network of the Central Vermont Public Service Corporation.

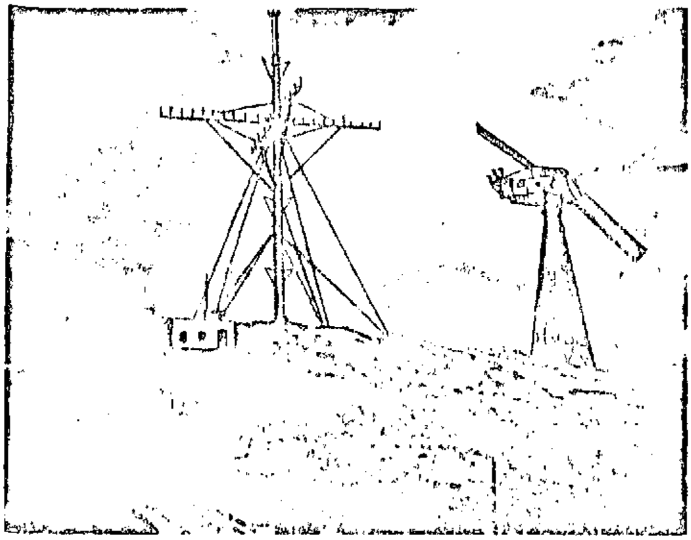

Fig. 26. Smith-Putnam turbine installation at Grandpa's Knob, Vermont.

Right to left: 1,000 kV wind engine with metal scaffolding supporting the anemometers, the control station, the transformer and the output terminal of the high tension line.

The installation was put into test operation on October 19, 1941, and continued to operate until one of the blades on the main shaft was damaged. During this period the unit remained connected to the network for 695 hr and was disconnected for tests for 192 hr, producing a total of 298,240 kWh. Due to problems in obtaining equipment and questions of priority the damaged blade could not be replaced until March 3, 1945. Between March 3 and 26, the unit operated as an ordinary plant in the network for 143 hr and produced 61,780 kWh, despite a period of calm which was exceptional for March. On the last day of this period, while the engine was rotating under a moderate wind of 9 m/sec, a blade suddenly broke at the joint which bolted it to the main frame. The rupture was produced by a large number of fissures due to corrosion which had occurred at this point. The broken blade struck the ground several hundred meters away on the mountain, while the remaining blade struck the pylon and was damaged in turn.

Fissures due to corrosion were found in the same area on this blade.[5].

The Morgan Smith Company, which had financed the test installation, decided to abandon the project following this failure. Indeed, since 1945, extremely thorough cost price research has shown that it is still much more costly to produce power from wind than by other methods. The Central Vermont Public Service Corporation offered to pay $130/kW for a 10,000 kW unit to be assembled in the mountains of Vermont at an altitude of 1200 m. For its part, the Morgan Smith Company estimated on the basis of the Grandpa's Knob experiment that it could deliver a unit of this type for $190/kW without any profit to the company itself. Further research might have lowered this price to $180, but the tests which would have been necessary to assure that a decrease of this size would be possible would alone have required an investment of several hundred thousand dollars without any assurance of success. The company therefore decided not to pursue the tests and turned over its patents to the public domain [6].

Thus in the final analysis the Grandpa's Knob experiment terminated in at least a provisional failure. It was a failure from a technical standpoint in that the initial cause of the rupture was probably an inadequate estimate of the stresses exerted by wind on a metallic structure exposed to the elements; but it was especially an economic failure since the cost price of the installation was too high for it to be sold under normal conditions.

However, in our opinion there is absolutely no reason to abandon the possibility that wind power will take its proper place alongside other natural power sources. The Grandpa's Knob experiment was not lost effort; a further installation can be expected to avoid the defects of the first. Unfortunately, however, other types of defects may appear in the future. The familiar machines used are the product of decades of development during which it was necessary to eliminate a great many imperfections. Current attempts to develop the wind engine are proceeding at full speed, and some problems which had gone unnoticed or had been neglected in the low-power units constructed so far may suddenly reach unexpected magnitude. In this regard, the construction of a 1,000 kW unit would seem to be imprudent and subject to some risk. It is unfortunately in the nature of things that any accident affecting a wind engine almost inevitably results in its destruction or removal from operation.

As for the economic aspects, it may be noted that site selected, although it was favorable from the point of view the wind system, was much less so in regard to cost comparisons. The state of Vermont is heavily supplied with electricity and is close to powerful thermal or hydroelectric plants. The cost price comparison would undoubtedly have been less unfavorable to the wind engine if it could have been installed in an area less abundantly supplied with power sources. In any case, the American experience with a single prototype seems to indicate that an attractive cost price could be obtained by mass production. The problem is thus reduced to the construction of a completely developed prototype, a project which, due to the temporary failures which must be expected, will necessitate financial outlays which cannot be supplied either by individual inventors or by private companies, but which would involve the financial resources of government organizations.

The same may be said of the installations projected by the American engineer Percy H. Thomas of the Federal Energy Commission in Washington. This engineer has made a very detailed study of two 6500 and 7500 kW installations using two twin wheels, either with three blades (6500 kW) or with two blades (7500 kW), mounted in a single plane atop a hexagonal tower consisting of a tapered framework (Fig. 27). The two wheels use bevel gears to drive a single dc generator located in the power plant engine room. The current produced is transmitted to the network after being converted by a commutator. The total weight of this type of installation is about 1400 T. The cost price, based on the construction of ten identical units, would be $68/kW for the 7500 kW unit and $75/kW for the 6500 kW unit. So far no practical tests have been made.

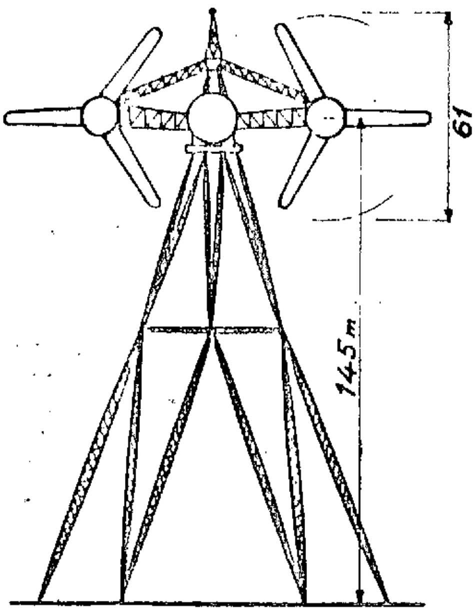

Fig. 27. 6500 kW wind engine project with two twin wheels, designed by Percy H. Thomas.

Obviously in France we are far behind the American experiments or even the most modest -- but tangible -- results obtained in Denmark with the Lykkegaard windmills. The last Wind Conference at Carcassonne (1946) [7] revealed no wind power units with a capacity of more than about 20 hp. Wind power is once more the object of sharp interest, however. According to our information several designers are currently researching or actually constructing projects which in some cases are on the scale of the American experiment, Moreover, the French Electrical Company has undertaken a vast program of research which notably includes a study of the capabilities of various types of known devices and the conditions for parallel operation of these devices in a network. One may therefore hope that in a few years we may know whether wind is actually capable of becoming a national power source along with fuel and hydroelectric power, or whether it should be limited to more modest tasks such as irrigation or the supply of low amounts of motive force to areas unable to obtain any other source of power, in colonies, for example; there is already a considerable market for this type of power production.

V. Conclusions

It should be emphasized that wind engines are now well beyond the theoretical stages. The characteristics of these engines -- at least those of the conventional model with radial blades, which seems to be the only one used for high-power projects -- are computed in the same way as those of gas turbines. Furthermore, a look at the accumulated French and foreign patents will confirm the fact that, discounting the obvious variations in design details, all the major theoretical ideas have been patented, frequently several times, since there are few machines which have so stimulated the minds of inventors. The wind engine problem no longer depends on the inventor, therefore; but has moved into the province of research firms and the computer. To repeat a statement which appeared earlier in this journal, the problem is no longer to invent wind engines, but to build and refine them -- and also, of course, to finance them. This is not the easiest part of the task.

We would like to thank the administration of the Electromechanics Company for allowing partial publication of the research it has performed since 1926 at the instigation of its chief engineer, Mr. Darrieus; this research has constituted a large contribution to study of the use of wind power.

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